How should "ambidexterity" be estimated?

Jacqueline Fagard, Amandine Chapelain, Philippe Bonnet

How should "ambidexterity" be estimated?

Jacqueline Fagard[1], Amandine Chapelain[2], and Philippe Bonnet[3]

[1]Laboratoire Psychologie de la Perception, Université Paris Descartes (UMR 8242), Paris, France
[2]EthoS – Éthologie animale et humaine, Université de Rennes 1, Rennes, France
[3]Laboratoire Vision Action Cognition, Université Paris Descartes (EAU01), Boulogne-Billancourt, France

Weak and absent hand preferences have often been associated with developmental disorders or with cognitive functioning in the typical population. The results of different studies in this area, however, are not always coherent. One likely reason for discrepancies in findings is the diversity of cut-offs used to define ambidexterity and mixed right- and mixed left-handedness. Establishing and applying a common criterion would constitute an important step on the way to producing systematically comparable results. We thus decided to try to identify criteria for classifying individuals ambidextrous, mixed right- or left-handed or strong right- or left-handed. For that purpose, we first administered a handedness questionnaire to 716 individuals and performed multiple correspondence analyses to define handedness groups. Twenty-four participants were categorized as ambidextrous (3.3%), as opposed to mixed (29.2%) and strong (56%) right-handers, and to mixed (9.1%) and strong (2.4%) left-handers. We then compared this categorization with laterality index (LI)-based categories using different cut-offs and found that it was most correlated with LI cut-offs at −90, −30, +30 and +90, successively delimiting strong left-handedness, mixed left-handedness, ambidexterity (−30 to +30), mixed right-handedness and strong right-handedness. The characteristics of ambidextrous and lateralized individuals are also compared.

Keywords: Ambidexterity; Mixed-handedness; Measurement; Gender; Family handedness.

Despite its continuous nature, handedness is often treated using a categorical approach in which different laterality groups are compared on a variety of

Address correspondence to: Jacqueline Fagard, Laboratoire Psychologie de la Perception, Université Paris Descartes, Paris, France. E-mail: jacqueline.fagard@parisdescartes.fr

No potential conflict of interest was reported by the authors.

factors. Such grouping may be helpful for statistical analyses and the evaluation of handedness-associated features. The population is commonly divided into two groups, such as right- versus left-handers or right- versus non-right-handers. However, finer categorizations often distinguish subpopulations, such as extreme, inconsistent, or mixed right- or left-handers and the ambidextrous. The criteria used to define these categories differ across studies. This makes it difficult to compare different studies and draw conclusions about the frequency of the various patterns of handedness. One group that is particularly poorly defined is that of the ambidextrous: the limit between ambidexterity and mixed right- (or left-) handedness is difficult to draw, as we will see below. The goal of the present study was to try to find a way to define this limit.

Etymologically speaking, an ambidextrous individual is one who has two (*ambi*) right hands (*dexter*)—in other words, who shows no preference for using one or the other hand when performing all or most activities. Such true ambidexterity may be astonishing, for instance when such an individual starts writing with the left hand on the left part of a blackboard and shifts to the right hand to continue writing on its right side. True ambidexterity is extremely rare. Ambidextrous individuals often end up choosing one hand for a given activity once they begin to practice it frequently. For instance, very few adults answer "either hand" when asked which hand they write with (Provins, Milner, & Kerr, 1982). Children may differ in this regard. A few personal communications from ambidextrous adults have indicated that, as children, they were often made uncomfortable by not knowing which hand to write with in class, especially when they were writing to a time limit and wasting precious time deciding which hand to write with. As adults, on the other hand, having chosen a writing hand, they no longer experience this problem, they report.

In theory, true ambidextrous individuals should be distinguished from non-lateralized mixed-handers—that is, individuals who systematically use one hand for some activities and the other hand for other activities. This category of mixed-handers has to be distinguished from mixed (sometimes called "inconsistent") right- or left-handers who clearly use more often one hand than the other. Even self-declared right- and left-handers are able to use their non-preferred hand in many situations when their preferred hand is busy, or the situation makes it uncomfortable for them to use it (Bryden, Pryde, & Roy, 1999, 2000; Bryden & Roy, 2006; Carlier, Doyen, & Lamard, 2006; Leconte & Fagard, 2004).

Thus, ambidexterity could be defined as the absence of a preference for either the right or the left hand when performing most activities (true ambidexterity) or the systematic use of one hand for certain activities and the other hand for other activities without any tendency to use one hand more often than the other (non-lateralized mixed-handers).

The continuum going from individuals who are completely lateralized in one or the other direction to the very rare truly ambidextrous individuals makes it difficult to draw a line between the different handedness groups. This continuum in handedness can easily be observed using tests evaluating the performance difference between the two hands (e.g., Annett, 1992). However, the fastest and easiest way to evaluate handedness rapidly is with a laterality questionnaire, in which the individuals indicate which hand they use to perform different tasks; and since handedness is often evaluated as a complement to the investigation of other parameters, finding criterion to distinguish ambidexterity from mixed right- and mixed left-handedness on a questionnaire would be useful.

There are a number of laterality questionnaires, including those of Annett (1976), Oldfield (the Edinburgh Inventory, 1971), Peters and Servos (1989) and Steenhuis and Bryden (1989), among others. The number of items is often around 10 but varies from 5 to 75. In some cases, the possible answers are only "left", "right" or "either hand", while in others respondents are also asked whether they use this hand always or most of the time. The larger the number of items used, the greater the chance that a respondent will indicate the non-preferred hand for some items (Provins et al., 1982; Satz & Green, 1999). In other words, not restricting the questionnaire items to a small number of well-practiced actions reduces the percentage of consistent right-handers and consistent left-handers. With a sufficiently large number of questions, although the shape of the handedness distribution remains asymmetrically bimodal, individuals can be found everywhere on the distribution (Annett, 1970a). On this continuous distribution, the closer an individual is to giving an equal proportion of "right-hand" and "left-hand" answers, or the greater the number of "either hand" answers, the closer he/she is to ambidexterity. The proportion of the population that is termed "ambidextrous" on the basis of a given handedness questionnaire will thus depend on the number of items and on the cut-off point.

A look at the literature shows that the categorization of individuals as weakly or not lateralized varies considerably between studies. Some studies classify individuals who are neither strong left-handers nor strong right-handers as ambidextrous. Strong right-handers may be defined as having a laterality index (LI)[1] greater than 75, and strong left-handers as having an LI lower than −75 on the Edinburgh Inventory, with all those in between considered ambidextrous (Knecht et al., 2000). In other studies, the cut-off for delimiting ambidexterity is set between +50 and −50 (Auer et al., 2009), between +40 and −40 (Li, Zhu, & Nuttall, 2003), between +20 and −20 (Cabinio et al., 2010) or between +15 and −15 (Barut, Ozer, Sevinc, Gumus, & Yunten, 2007) on the Edinburgh Inventory or a modified version of it. In another study, only participants who reported using

[1] Laterality index (LI) is usually calculated as [number of right-hand responses – number of left-hand responses/total number of responses], and varies between 1 (completely right-handed) and –1 (completely left-handed), or between –100 and 100 if the LI is multiplied by 100. We will follow the latter convention here.

the same hand for 10 out of 12 items were categorized as right- or left-handers, with all others classified as mixed-handers (Mori, Iteya, & Gabbard, 2006).

The criteria for strong handedness sometimes also differ between right- and left-handers, as in another study where participants were classified as right-handed if their LI on an 8-item handedness inventory was greater than +75 and left-handed if their LI was lower than −50 (Ponton, 1987). Similarly, Hatta and Kawakami (1995) classified individuals who performed at least 8 out of 10 items with the right hand as right-handers and individuals who performed at least 4 out of 10 items with the left hand as left-handers, leading to an asymmetric definition of "ambidextrous". In another study, participants who reported performing between 2 and 6 out of 8 items with their left hand were labelled "inconsistent left-handers" (Gardner & Potts, 2010). In one study, ambidextrous individuals were grouped together with left-handers as "non-right-handers" and opposed to right-handers, defined by an LI cut-off of +.50 (Szaflarski et al., 2002).

The term "ambidextrous" is sometimes used as a synonym for inconsistent or mixed-handedness (Auer et al., 2009). Occasionally, only self-report of ambidexterity is used (Bryden, Bruyn, & Fletcher, 2005), or, in children, handedness may be based on parental report (Rodriguez et al., 2010). Sometimes the criterion is simply not specified (Slezicki et al., 2009). In sum, the same handedness labels correspond to different criteria across studies. And in general, cut-offs are chosen empirically, not on theoretical grounds. Clearly, a criterion for defining ambidextrous individuals and distinguishing them from mixed right- and mixed left-handers is needed, which is the goal of the present study. A common and precise criterion may help clarify the conflicting results on associations between patterns of hand preference and cognitive characteristics (see, for instance, Denny, 2008; Halpern, Haviland, & Killian, 1998; Kopiez, Galley, & Lee, 2006; McKeever, 1986).

Left-handedness has long been associated with developmental disorders (Batheja & McManus, 1985; Carlier, Stefanini, et al., 2006) or with less optimum development in the typical population (Johnston, Nicholls, Shah, & Shields, 2009). It now seems evident that it is a lack of hand preference, more than left-handedness, that is often linked to developmental disorders (see, for instance, Cornish & McManus, 1996; Domellöf, Ronnqvist, Titran, Esseily, & Fagard, 2009; Soper, 1986) and to cognitive disadvantage in typically developing children (Johnston et al., 2009). Concerning adults, there has also been a shift from the idea of left-handedness influencing cognitive skills, most often negatively (Annett & Kilshaw, 1982; Benbow, 1986, 1987; Halpern et al., 1998; McKeever, 1986; McManus, 2002), to the notion that it is the presence or absence of a clear hand preference (or of clear difference of performance between the two hands) that is related to differences in cognitive abilities (Corballis, Hattie, & Fletcher, 2008; Crow, Crow, Done, & Leask, 1998; Orton, 1937; Peters, Reimers, & Manning, 2006; Prichard, Propper, & Christman, 2013).

However, for adults the evidence is mixed (Denny, 2008; Mayringer & Wimmer, 2002), and a positive effect of mixed-handedness on one skill (musical sight reading) has even been observed (Kopiez et al., 2006). In fact, the observed relationships between lack of clear hand preference and cognitive functioning vary depending on the stringency of the adopted definition of ambidexterity (Annett, 1998; Crow et al., 1998; Giotakos, 2002). It is thus important to operationally distinguish the ambidextrous persons from other laterality groups, to check whether ambidexterity is associated with cognitive disadvantage (or advantage).

In order to find a criterion to evaluate ambidexterity, as opposed to mixed right- and left-handedness, we used a questionnaire that was either sent by e-mail or given directly to the person. A questionnaire was used in order to contact the greatest possible number of participants, and because it has been shown to be a reliable method for testing handedness in adults (Coren & Porac, 1978; Raczkowski, Kalat, & Nebes, 1974). We analysed the clustering of the responses in order to determine the best cut-off to distinguish the different handedness groups. In this article, the term "ambidextrous" will be used to refer both to individuals who are truly ambidextrous—i.e., who choose "either hand" for a majority of the handedness items—and to non-lateralized mixed-handers—i.e., who systematically choose one hand for some activities and the other hand for other activities without any overall tendency to choose one hand more than the other. Mixed right- and left-handers will in turn be contrasted with strong right- and left-handers.

METHOD

Participants

The results bear on 716 adults. We collected a slightly larger number of questionnaires, but a questionnaire was immediately discarded when information about hand preference had not been correctly filled and we could not reach the respondent. All participants who completed at least 12 out of the 15 handedness items were included. Most participants filled in all 15 items (N = 684); 27 participants filled in 14 items, 3 participants filled in 13 items and 2 participants filled in 12 items. For the items that are the most widely studied in the literature (writing, hammer and ball), there were no missing responses.

The participants ranged in age from 18 to 73 years (mean age: 30.7 years, *SD*: 11.9). For some analyses, in order to check whether the frequency of ambidexterity changes with age, participants were categorized into two age groups: a younger group (less than 28 years old) and an older group (28 years old or more). Substantially more women (62.3%) than men (36.7%) answered the questionnaire. The mean age was similar for women (30.8 years, *SD*: 11.8) and men (30.3 years, *SD*: 12.3). The imbalanced male/female ratio may partly be due to a difference in willingness to participate in the study, and it may also reflect the fact that there are more female than male students in the psychology department where a portion of the participants were recruited. The gender ratio was comparable in the two age groups, as indicated by a chi-square test, which showed no significant difference in the gender ratio between the two age groups. The majority of the participants were French citizens or were living in France (74.2%), but 25.8% of participants were British or were living in England, due to one of the authors (AC) being a Ph.D. student in England at the time of the study. Nationality information was missing for 54 individuals (7.5%). There was no significant difference in gender ratio between French and British participants, but the British participants were younger, on average, than the French participants (24.8 years and 33.2 years, respectively). Thus, 79.4% of British belonged to the younger age group whereas 51.9% of French belonged to the older age group (51.9%), and this difference is significant, $\chi^2(1) = 50$, $p < .00001$.

The frequency of left-handed parents was almost twice as high in the younger group (17.2%) as in the older group (9.3%). This difference was significant, as indicated by a chi-square test, $\chi^2(2) = 13$, $p < .01$. Slightly over one in 12 participants (8.5%) declared that they had been prevented from using their left hand as a child. The probability of experiencing this type of pressure was unrelated to gender, age or nationality.

Questionnaire

The questions included 15 handedness items, most of them taken from the main handedness questionnaires (Annett, 1970a; Corey, Hurley, & Foundas, 2001; Oldfield, 1971; Steenhuis & Bryden, 1989). Following recommendations from recent studies analysing some of these questionnaires (Busch, Hagemann, & Bender, 2010; Dragovic & Hammond, 2007), we also included items from relatively new habits. Participants were asked "With which hand do you…" "write", "brush your teeth", "throw a ball", "use a hammer", "hold a racket", "hold your hair brush", "hold a spoon to eat", "use a tissue to wipe your face", "play marbles", "hold the scissors to cut", "hold the stapler to staple", "open a drinks can (hand that pulls the opening)", "hold a vegetable peeler (hand that holds the instrument)", "use the computer mouse" and "press the buttons of the TV remote control". The participant was supposed to mark off one of three possible answers: left hand, either hand or right hand. We choose a simple answer because it has been shown that the reliability of the answer decreases as the number of choices increases (Coren & Porac, 1978; McMeekan & Lishman, 1975; Papadatou-Pastou, Martin, & Munafò, 2013; Raczkowski et al., 1974).

Other items included one foot item: "With which foot do you kick a ball?"; one eye item: "With which eye do you look through a telescope (to check, roll up a sheet of paper and look through at a distant object)?"; and one ear item: "With which ear do you listen behind a door?" The three possible answers for these items were, as for the manual items, left, either or right (foot, eye or ear).

Finally, there were a few more questions: "Were you ever prevented from using your left hand as a child?" (Answers: "yes" or "no.") Another question was "Are there left-handers in your family?" (Answers: "Father", "Mother", "Other.") In addition, the participants were also asked to give their age, gender, nationality and occupation.

Data analysis method

We first divided individuals into clusters according to their responses to the manual items and identified an ambidextrous group apart from the mixed left-handed, mixed right-handed and strong left- and right-handed groups. We then analysed to what extent the ambidextrous group differ from the lateralized groups with respect to the independent factors, on the one hand—age, gender, nationality, parents' handedness and restriction from using the left hand in childhood—and with respect to the other measures of asymmetry, on the other hand—preferred eye, ear and foot.

Participants were classified using geometric data analysis (GDA; Le Roux & Rouanet, 2004). The basic data set is an Individuals × Variables table, where each question constitutes a variable composed of three categories, i.e., "right", "left", "either." Since some participants did not answer all questions, a fourth category ("no answer") had to be created for the 11 questions where this occurred. These "no answer" categories were infrequent categories here. This table was analysed with the GDA method of multiple correspondence analysis (MCA), more precisely a variant of MCA called specific MCA (Le Roux & Rouanet, 2010). Infrequent categories of active variables are a problem for specific MCA. They participate heavily in the contribution of the variable and they can be overly influential for the determination of axes. As far as these infrequent "no answer" categories cannot be pooled with some other categories, it is possible, in order to preserve the constitutive properties of MCA, to resort to specific MCA that ignores these categories for the determination of distances between individuals. Two specific MCAs were applied to the data.

In our first MCA, we entered 716 individuals and 15 questions with 56 corresponding categories, including 45 active categories and 11 passive ("no answer") categories. The presentation of the basic results will be as follows: the variances of axes (eigenvalues); the contributions of categories to the variance of axes; and the geometric representation of two clouds: the cloud of categories and the cloud of individuals.

Owing to the high dimensionality of clouds in MCA, the variance rates of the first principal axes are usually quite low. In order to better appreciate the importance (which is not a variance rate) of the first axes, Benzécri (1992) proposed to use modified rates. The first two axes will be interpreted, this choice being based on the decrease of variances (eigenvalues) and the cumulated modified rates (first axis 93.9%, second axis 5%). We did not try to select the categories that made the largest contributions here; however, since the interpretation of the axes is fairly obvious. The aim of the study was to define ambidexterity, not to analyse the contributions of particular items on handedness questionnaires.

RESULTS

Classification of individuals by handedness

Interpretation of Axis 1. In the cloud of categories (see Figure 1), all the "right-hand" categories are on the right side of the axis, and all the "left-hand" categories are on the opposite side with large contributions (see Table 1). In between are the "either" categories with very weak contributions. This axis can be interpreted as a laterality axis. This can be confirmed by computing the mean point of all "right-hand" categories (black square labelled RIGHT-HAND in Figure 1) and the mean point of all "left-hand" categories (black square labelled LEFT-HAND in Figure 1). We can then calculate the contribution of the deviation between these two mean points to the variance of the axis. This contribution accounts for 97.1% of the variance of the first axis. It means that this opposition between these two mean points is a good summary for this axis.

Interpretation of Axis 2. The categories that contributed most to variance of Axis 2 are the "either" categories: these categories are located on the negative side of this axis (towards the bottom). This axis opposes these "either" categories to all others ("right-hand" and "left-hand"); that is, lesser laterality to clear laterality. To confirm this interpretation we compute two mean points: one for the "either" categories (black square labelled EITHER in Figure 1) and the other for all other categories (not shown in Figure 1). Therefore the contribution of the deviation between these two mean points accounts for 88.3% of the variance along Axis 2.

Exploration of the cloud of individuals. A first examination of the cloud of 716 individuals in planes 1–2 shows greater concentration on the right (right-handers) and more scattering on the left (left-handers). The distribution as a whole is triangular (see Figure 2) like the cloud of categories. Strongly right-handed individuals are defined as having 14 or 15 "right" answers to the 15 items of the questionnaire. Similarly strongly left-handed individuals are defined as having 14 or 15 "left" answers to the 15 items of the questionnaire. Moving from right to left across planes 1–2, we first find strongly right-handed individuals, who make up the great majority (400 out of 716). At the opposite end are strongly left-handed individuals, who are more scattered and less numerous (17 out of

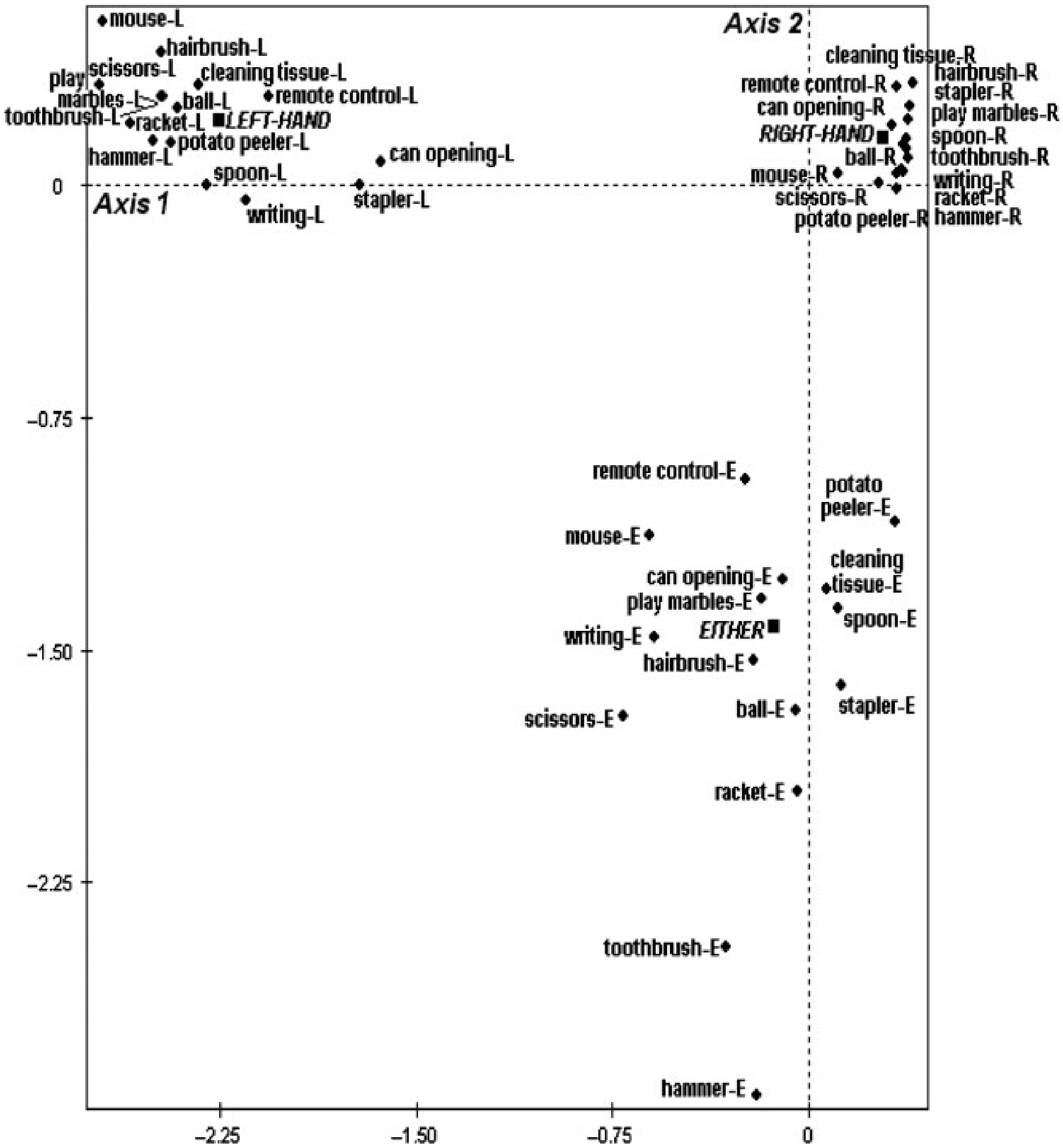

Figure 1. Cloud of categories: items categories are labelled L for "left", R for "right" and E for "either".

716). Then, moving from bottom to top, we find the very few individuals who use either hand, followed by individuals who use their right hand for some items and their left hand for other items.

There are at least two ways of defining mixed-handedness using responses to the questionnaire: as "either" responses to most of the 15 items, or as equivalent numbers of "right-hand" and "left-hand" responses. The "either" respondents are located at the bottom of Axis 2, while the mixed "right-hand" and "left-hand" respondents are in the upper part of Axis 2, between the right pole and the left pole along Axis 1.

As we interpreted the first axis as an axis of laterality, an individual's coordinate on Axis 1 can be considered as an index of laterality. An extreme

TABLE 1
Contributions (in %) of categories to the first two axes

Question	*Category*	*Axis 1*	*Axis 2*	*Question*	*Category*	*Axis 1*	*Axis 2*
Writing	Right	0.927	0.038	Cleaning tissue	Right	1.020	2.421
	Either	0.057	1.201		Either	0.008	11.206
	Left	5.749	0.011		Left	6.231	0.423
Toothbrush	Right	1.145	0.227	Play marbles	Right	1.023	0.573
	Either	0.044	9.120		Either	0.034	6.380
	Left	7.159	0.341		Left	6.384	0.298
Ball	Right	1.008	0.448	Scissors	Right	0.622	0.001
	Either	0.002	7.585		Either	0.088	1.795
	Left	6.645	0.244		Left	5.850	0.292
Remote control	Right	0.729	2.244	Stapler	Right	1.019	1.082
	Either	0.137	7.440		Either	0.013	8.313
	Left	3.214	0.211		Left	4.752	0.000
Hammer	Right	1.087	0.050	Can opener	Right	0.703	0.943
	Either	0.007	5.285		Either	0.011	6.607
	Left	7.422	0.085		Left	3.428	0.024
Racket	Right	1.007	0.076	Potato peeler	Right	0.937	0.005
	Either	0.001	4.316		Either	0.001	0.055
	Left	7.430	0.155		Left	6.894	0.073
Hairbrush	Right	1.064	1.619	Mouse	Right	0.105	0.039
	Either	0.064	11.531		Either	0.151	1.798
	Left	6.011	0.627		Left	1.958	0.259
Spoon	Right	1.073	0.363				
	Either	0.008	4.197				
	Left	6.777	0.000				

Contributions of categories that are greater than the average contribution (here 100/45 = 2.22) are given in shading.

positive coordinate on Axis 1 reflects consistent or strong right-handedness and an extreme negative coordinate consistent or strong left-handedness. In between are individuals with some “right-hand” responses and some “left-hand” responses or “either” responses. An individual who gave more “left-hand” than “right-hand” responses will be towards the left side of Axis 1, and one with the opposite pattern will be located towards the right side.

To verify this interpretation, we calculated the correlation between the coordinates of individuals on Axis 1 and a separately computed LI, $r = 0.98$. This correlation is very high, confirming our interpretation of the first axis.

At this stage, three groups were to be defined: right-handed individuals, left-handed individuals and mixed-handed individuals (including, at this stage of the analysis, ambidextrous individuals, mixed right-handers and mixed left-handers). To do so, a Euclidean clustering (ascending hierarchical clustering) was performed, on the basis of the first two coordinates obtained by MCA, with variance as the aggregation index (Ward’s method). A partition into three classes

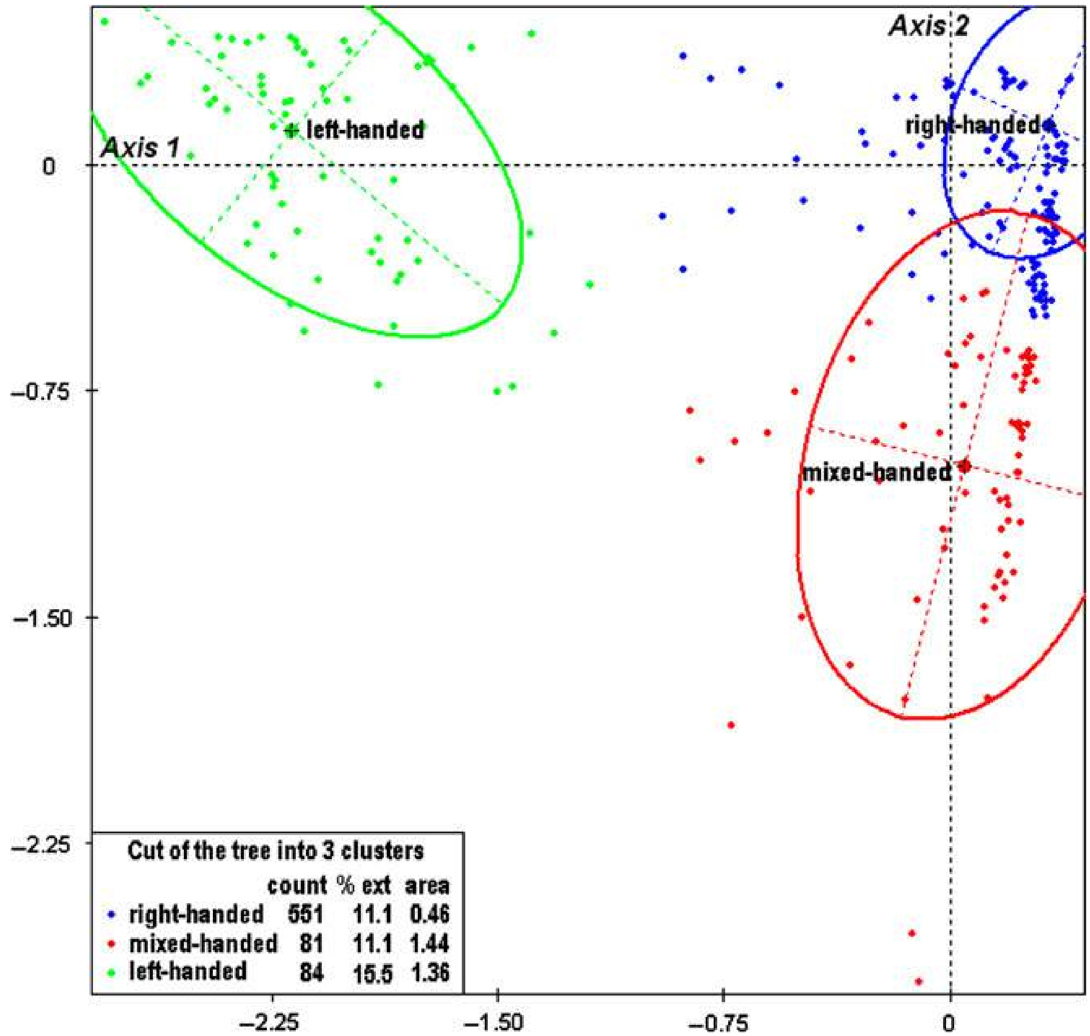

Figure 2. The three clusters of individuals with their concentration ellipses.

was retained, which accounts for 86% of the variance of the cloud. The three subclouds with their concentration ellipses are shown in Figure 3. The first dichotomy is by far the most important one (71.5%); it separates the left-handed individuals (n = 84) from others. The second dichotomy, much less important (14.9%), separates the right-handed individuals (n = 551) from a third group we called mixed-handed (n = 81).

As can be seen in Figure 2, the most concentrated group is the "right-handed" group; the "left-handed" and "mixed-handed" groups are more scattered.

Next among the mixed-handed individuals, we sought to distinguish between ambidextrous, rightward mixed-handed and leftward mixed-handed individuals. To do this, we performed a second analysis of the same type (MCA).

Individuals having given "right-hand" (n = 400) or "left-hand" (n = 17) responses to 14 or 15 out of the 15 items were excluded from this second analysis. We thus entered 299 individuals and the same 15 items as before. A

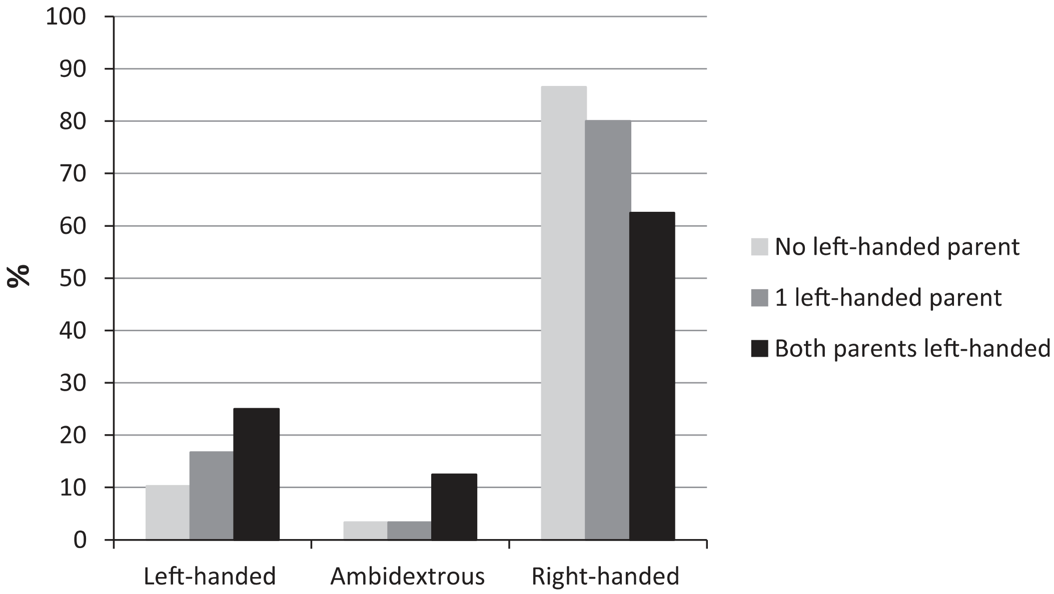

Figure 3. Handedness of the offspring as a function of parents' handedness.

specific MCA was carried out, and this second analysis gave similar results with a very important first axis (95%), still a laterality axis. The second axis opposes the "either" categories to the two other categories (right and left hand). Doing again a Euclidean clustering on the basis of the first two coordinates obtained through this second MCA, a partition into three classes emerged which accounted for 85% of the variance of the cloud. The first dichotomy separates a class of left-handers from the others. Then a second dichotomy divides the others into two clusters, one consisting of right-handers and the other of mixed-handed individuals. Within this class of mixed-handed individuals 24 individuals were categorized as ambidextrous, others being categorized as mixed right-handed.

In summary, out of 716 individuals, 24 were categorized as ambidextrous (3.3%), 610 were categorized as right-handed (85.2%), among which 401 were strongly right-handed (56%) and 209 were mixed right-handed (29.2%). Eighty-two were categorized as left-handed (11.6%), among which 17 were strongly left-handed (2.4%) and 65 were mixed left-handed (9%).

Comparison of categorization as ambidextrous depending of criteria

To find the best way to categorize ambidextrous individuals easily on the basis of the LI, we used a procedure in several steps: first we compared the classification of ambidextrous individuals obtained from the MCA to the classification obtained from the LI using several different cut-offs; second, in order to choose the best cut-off among those best correlated with the MCA, we identified all participants whose respective percentage of “either”, “right” and “left” responses should lead them to be considered ambidextrous according to the definition given above in the Introduction (having no hand preference for most activities and/or systematically choosing one hand for some activities and the other hand for other activities without any overall tendency to choose one hand more often than the other); finally, we checked which cut-off, among those that were well correlated with the MCA, included all the ambidextrous individuals who were identified as such according to our definition.

The LI of the 24 ambidextrous individuals categorized by the MCA ranged from −20 to +53. We checked how many of them would have been included in this category had we set the cut-off directly at [−10, +10], [−20, +20], [−30, +30], [−40, +40] or [−50, +50], which are the main cut-offs found in the literature. We also added an asymmetrical cut-off within the limits of the LI of our ambidextrous participants (−20 to +55); and, since most studies using an asymmetrical cut-off have set the limit closer to zero for negative values than for positive values, we also added the opposite cut-off (−55 to +20). Table 2 shows that our classification was highly correlated with [−20, +20], [−30, +30] and [−40, +40] cut-offs and the least correlated with [−10, +10] and [−55, +20] cut-offs.

Before choosing between the [−20, +20], [−30, +30] and [−40, +40] cut-offs, we analysed which participants would be classified as ambidextrous if we set a criterion as a function of the ratio of “either” responses to “right” and “left” responses, and as a function of the ratio of “left” to “right” responses (our two criteria for ambidexterity). Had we included only participants having given a majority of “either” responses, only four (0.56%) would have been categorized as ambidextrous. These participants would be true ambidextrous individuals, who are equally likely to perform the majority of actions with either the left or the right hand. Including participants who chose equivalent numbers of “left” and “right” responses (±2) led to the identification of 10 individuals as ambidextrous. One had already been classified as true ambidextrous, since he gave 8 “either” responses, 4 “left” responses and 3 “right” responses: i.e., a majority of “either” responses, as well as nearly equal numbers of “left” and “right” responses (difference of 1). The nine additional individuals classified as ambidextrous by this second criterion did not give a majority of “either”

TABLE 2

Correlations between classifications provided by our statistical analysis and the cut-offs most frequently used to determine ambidexterity

LI cut-offs	*−10 to + 10*	*−20 to +20*	*−30 to +30*	*−40 to +40*	*−50 to +50*	*−20 to 55*	*−55 to +20*
Our classification from the statistical analyses	.45	.72	.71	.74	.66	.69	.49

responses, but did give nearly equal numbers of “right” and “left” responses, with a difference no greater than 2. As set out in the Introduction, these participants are non-lateralized mixed-handers. These nine participants, added to the four true ambidextrous individuals, gave a total of 13 participants (1.8%) who would be considered ambidextrous according to at least one of the two criteria.

We then looked at which of the [−20, +20], [−30, +30] and [−40, +40] cut-offs included these 13 individuals. The [−20, +20] cut-off included only 12 of these 13 individuals, starting with the [−30, +30], all 13 individuals were included as ambidextrous, in addition to a portion of the ambidextrous individuals as defined through the MCA. We concluded that the [−30, +30] cut-off is a valuable compromise to avoid having to perform a lengthy MCA procedure and to obtain a faster categorization on the basis of the LI. With a [−30, +30] cut-off, all ambidextrous individuals who either gave a majority of “either” responses or a nearly equal number of “left” and “right” responses were included, in addition to the majority of the individuals defined as ambidextrous on the basis of the MCA. Using this [−30, +30] cut-off, 22 participants (3.1%) were categorized as ambidextrous.

We then looked for a suitable cut-off to distinguish rightward and leftward mixed-handedness from strong handedness. To do so, we compared the classification of mixed- and strong handers obtained through the MCA with the classification obtained from a set of LI cut-offs. The LI defined through the MCA ranged from 20 to 92.7 for mixed right-handers and from −6.7 to −86.7 for mixed left-handers. We checked how these mixed-handers would be categorized had we set the cut-off directly at [−66, +66], as in Steenhuis and Bryden (1989). We also tested a classification using [−70, +70], [−80, +80] or [−90, +90], with −30 and +30 maintained as the limit for ambidexterity in all cases. As can be seen in Table 3, the strongest correlation with the MCA classification of mixed left- and right-handers was with the [−90 to −30, +30 to +90] cut-off.

The classification of all participants into five categories delimited by [90] and [30] resulted, in addition to the identification of 22 ambidextrous participants (3.1%), 616 right-handers (86%)—including 377 strong right-handers (52.6%)

TABLE 3
Correlations between classifications provided by our statistical analysis and the cut-offs most frequently used to determine mixed right- and left-handedness

LI cut-offs	*−66 to −30 and +30 to +66*	*−70 to −30 and +30 to +70*	*−80 to −30 and +30 to +80*	*−90 to −30 and +30 to +90*
Our classification from the statistical analyses	0.89	0.90	0.91	0.94

and 239 mixed right-handers (33.4%)—and 78 left-handers (10.9%), among them 9 strong left-handers (1.3%) and 69 mixed left-handers (9.6%). The correlation between the MCA-based distribution of the five handedness groups and the distribution calculated using [−100 to −90; −89.9 to −29.9; −30 to +30; +30.1 to +89.9 and +90 to +100] as ranges for strong left-handers, mixed left-handers, ambidextrous, mixed right-handers and strong right-handers, respectively, was .97. Only 7.3% of the participants change categories when these cut-offs are used instead of the MCA, and these changes are restricted to contiguous categories.

Analysis of the ambidextrous compared with right- and left-handers

A second goal of the study was to analyse the profile of the different laterality groups categorized with our procedure, in particular to compare the 24 ambidextrous individuals defined using the MCA with the other laterality groups. In what follows, whenever the analyses are described as comparing ambidextrous individuals with right- or left-handers without further specification, all right- or left-handers, both strongly lateralized and mixed-handed, were included. For some analyses we compared ambidextrous individuals with some or all of the four subgroups of mixed and strongly right- and left-handed. For all the analyses, we used the categorization into three or five groups given by the MCA. However we systematically checked whether the results held when using the [−90, −30, +30, +90] cut-off. Almost all of the statistics shown below are valid for both categorizations; we report the results from the [−90, −30, +30, +90] categorization only when they differ from the MCA results.

First, we verified that LI significantly distinguished the handedness groups. The mean LI of ambidextrous individuals was 17.6 (SD = 18.7), as opposed to −67.2 (SD = 20.9) for left-handers, and 89.6 (SD = 13.8) for right-handers. When the five handedness groups were distinguished, the LIs of the strongly left-handed and mixed left-handed groups were −92.9 (SD = 6.4) and −60.5 (SD = 18) respectively, and those of the strongly right-handed and mixed right-handed groups were 97.6 (SD = 4.1) and 74.3 (SD = 13.1) respectively. An analysis of variance (ANOVA) showed that LI differed significantly between groups, $F(4, 711) = 4781.8$; $p < .00001$, and least significant difference (LSD) post hoc tests indicated that all groups differed from each other.

In relation to the 15 manual items, ambidextrous individuals differed from the two lateralized groups in giving a greater mean number of “either (hand)” responses (see Table 4), as could be expected. An ANOVA with group as a between-subjects variable (N = 5) showed a significant effect of group on number of “either” responses, $F(4, 711) = 214$; $p < .001$. LSD post hoc tests indicated that all groups differed from each other on this variable, except strong right-handers and strong left-handers, who did not differ from each other.

TABLE 4
Mean number of “either hand” answers by handedness group

	Mean number of “either hand” answers (SD)	*Lower–higher value (maximum: 15)*
Strongly right-handers (N = 401)	0.2 (.4)	0–1
Mixed right-handers (N = 209)	2.8 (1.7)	0–8
Ambidextrous (N = 24)	4.1 (3.1)	0–11
Mixed left-handers (N = 65)	1.5 (1.3)	0–4
Strongly left-handers (N = 17)	0.1 (.3)	0–1

The percentage of “either” answers varied among the different items (see Table 5). “Hold a vegetable peeler” received the lowest percentage of “either” answers for left-handers, ambidextrous and right-handers (0%, 0% and 0.2%, for the three groups, respectively). “Hold a hammer” was next for right-handers (0.9%) and left-handers (1.2%), followed by “Write” for right-handers (1.1%), whereas 3.7% of left-handers and 8.3% of ambidextrous individuals gave an “either” response to this item. The items with the largest number of “either” answers were “Press the buttons of the TV remote control” for right-handers (21.9%) and left-handers (36.4%) and “Use cotton wool to clean your face” for ambidextrous individuals (54.2%). In order to check whether there was some consistency among handedness groups in the ranking of the items by frequency of “either” answers, we calculated a correlation between the ranking of items

TABLE 5
Percentage of participants having given an “either” response, by handedness group and item

	All	*Left-handers (%)*	*Ambidextrous (%)*	*Right-handers (%)*
Peeler	0.1	0	0	0.2
Writing	1.7	3.7	8.3	1.1
Hammer	1.8	1.2[a]	25	0.9[a]
Scissors	1.8	3.7	12.5	1.1[a]
Racket	3.3	1.2[a]	29.2	2.6[a]
Computer mouse	4.2	9.7	8.3	3.3
Toothbrush	4.5	4.9[a]	41.7	2[a]
Spoon	6.7	2.4[a]	16.7	6.9
Ball	7.8	4.9[a]	29.2	7.4
Stapler	9.5	2.4[a]	25	9.8
Marbles	10.6	9.8[a]	41.7	9.5
Can opening	12.1	12.2	20.8	11.8
Hair brush	14.5	18.3[a]	45.8	12.8
Cotton wool	19.5	8.5[a]	54.2	19.7
Remote control	24.4	36.4	50	21.9

[a]Indicates a significant difference from the ambidextrous group.

among left-handers, the ambidextrous and right-handers. The correlations were .53 between left-handers and the ambidextrous, .72 between the ambidextrous and right-handers and .75 between left-handers and right-handers. All three correlations are significant (p < .01). Finally, the ambidextrous gave a larger number of "either" answers than mixed right- and left-handers on almost all items (except "Peeler" and "Computer mouse"), but the difference was not always significant).

Although there was a main effect of age on group, N = 3, left-handers vs. ambidextrous vs. right-handers, $F(2, 702) = 5.4$; $p = .005$, a LSD post hoc test indicated that the difference was significant only between left-handers and right-handers, right-handers being younger than left-handers (see Table 6). The ages of the ambidextrous and lateralized groups did not significantly differ. Similarly, when the division into five groups was used for the analysis, the ambidextrous did not differ from any of the other groups in terms of age.

Concerning gender, the percentage of ambidextrous participants was greater among males (5.3% of males) than among females (2.2% of females). A binomial test indicated that this difference was significant. The percentage of right-handers tended to be lower among males (82.1%) than females (87%), whereas the percentage of left-handers tended to be higher among males (12.5%) than females (10.8%). However in both cases, binomial tests failed to show a significant difference. A chi-square test comparing the frequency of the three handedness categories (left-handed, ambidextrous and right-handed) by gender failed to reach significance (p = .06), but a chi-square test comparing ambidextrous participants with all lateralized participants combined (right- and left-handers pooled together) showed a significant effect, $\chi^2(1) = 4.8$; $p = .03$. Thus, the percentage of ambidextrous is significantly greater among males than among females when the ambidextrous are compared with all lateralized individuals. The effect remained significant when the ambidextrous were compared with right-handers, $\chi^2(1) = 5.1$; $p = .02$, but not when they were compared with left-handers. In sum, there were significantly fewer right-handed males and significantly more ambidextrous males than females in the same categories. (The same chi-square test comparing ambidextrous participants with all lateralized participants using the [−30, +30] LI cut-off failed to reach significance, $p = .08$)

The frequency of ambidexterity did not differ by origin: the proportion of ambidextrous among the French (3.5%) and the English (2.3%) was comparable. Six hundred and seventy-six participants answered the question about being prevented from using their left hand in childhood. A chi-square test on the frequency of yes/no responses by group (N = 5) showed that pressure varied significantly between groups, $\chi^2(4) = 27.9$; $p < .000$. Pressure was reported more frequently by the ambidextrous, followed by mixed left-handers, then by mixed right-handers, and the least frequently by strong right- and left-handers. A 2 × 2 comparison showed that

TABLE 6

Independent and dependent variables by handedness group

	Strongly left-handed	*Mixed left-handed*	*Ambidextrous*	*Mixed right-handed*	*Strongly right-handed*
Number of individuals (% of 716)	17 (2.4%)	65 (9.1%)	24 (3.3%)	209 (29.2%)	401 (56%)
Mean LI	−92.9 (6.4)	−60.5 (18)	17.6 (18.7)	74.3 (13.1)	97.6 (4.1)
Age	34.8 (13.2)		29.9 (13.7)	30.2 (11.7)	
% of the male population	12.5%		5.3%	82.1%	
% of the female population	10.8%		2.2%	87%	
Pressure reported (% of each group)	6.7%	19.3%	34.8%	9%	6.6%
"	16.9%		"	7.5%	
% of the 613 families with no left-handed parents	2.1%	8.2%	3.3%	28.1%	58.4%
"	10.3%		"	86.5%	
% of the 90 families with one left-handed parent	4.4%	12.2%	3.3%	35.6%	44.4%
"	16.7%		"	80%	
% of the 8 families with two left-handed parents	0%	25%	12.5%	50%	12.5%
	25%		"	62.5%	
For each result reported below: % of each group					
Right-hand writing	0%	16.9%	33.3%	92.3%	99.7%
	13.4%		"	97.2%	
Left-hand writing	94.1%	80%	58.3%	4.3%	0.23%
	82.9%		"	1.6%	
Right foot (shooting)	13.3%	23.6%	54.5%	59.3%	84.7%
	21.4%		"	75.8%	
Left foot (shooting)	80%	56.4%	13.6%	5.6%	3.4%
	61.4%		"	4.2%	
Right eye	25%	29.2%	39.1%	65.2%	66.3%
	28.4%			65.9%	
Left eye	75%	63.1%	52.2%	26.6%	26.8%
"	65.4%		"	26.7%	

(*continued overleaf*)

TABLE 6
(*Continued*)

	Strongly left-handed	*Mixed left-handed*	*Ambidextrous*	*Mixed right-handed*	*Strongly right-handed*
Crossed hand-eye	25%	31.7%	50%	28.9%	28.80%
"	30.3%		"	28.8%	
Crossed hand–foot	14.3%	29.5%	28.6%	8.7%	3.8%
	25.9%		"	5.2%	
Right ear	0%	24.6%	30%	44.7%	57.9%
"	19.2%		"	53.4%	
Left ear	81.3%	43.9%	30%	20.5%	19.7%
	52.1%		"	19.96%	

ambidextrous participants reported significantly more pressure than right-handers $\chi^2(1) = 21.2$; $p < .00001$, and but not left-handers, $p = .06$.

Most participants reported their parents' handedness (99.3%). Eighty-six per cent had no left-handed parents, 8.4% had a left-handed father ($N = 60$), 4.2% had a left-handed mother ($N = 30$) and 1.1% ($N = 8$) had two left-handed parents. Thus, participants were twice more likely to report having a left-handed father than a left-handed mother. A binomial test showed that when one parent was reported as left-handed, the chance that it would be the father significantly differed from 50% ($p < .01$). The chance that a participant who reported having a left-handed mother would also be left-handed (20%) was higher than the corresponding percentage for those who reported having a left-handed father (15%) but a binomial test showed that the 15% of 60 participants reporting a left-handed father did not differ significantly from 20% of 30 reporting a left-handed mother. We thus pooled the participants whose father or mother was left-handed. The frequency of right-handers decreased with the number of left-handed parents whereas the frequency of ambidextrous and left-handers increased. A chi-square on the type of offspring (× 2, non-right-handers (left-handed + ambidextrous) versus right-handers) by parents' handedness (× 3: no left-handed parent, 1 left-handed parent, 2 left-handed parents) was significant, $\chi^2(2) = 6$; $p = .049$. Participants with two left-handed parents were 2.5 times more likely to be ambidextrous and 2.7 times more likely to be left-handed than those with no left-handed parent (see Figure 3).

Finally we checked whether the other lateralities—eye, foot and ear—differed between the groups defined on manual laterality. The frequency of use of the right effector/receptor to look through a telescope, kick a ball and listen behind a door decreased regularly and significantly from strong right- to strong left-handers, with a highly significant effect even with the division of participants into five groups (see Table 6). Chi-square tests on the relationship between response (× 3: left, either, right) and laterality group (× 5) showed significant effects for the eye, $\chi^2(8) = 57.1$, $p < .00001$; foot, $\chi^2(8) = 257.1$, $p < .00001$; and ear, $\chi^2(8) = 136$; $p < .001$.

Significantly more ambidextrous participants gave "either" answers for the foot (29%) than strong right-handers (9.7%); $\chi^2(1) = 8.9$, $p = .003$, and almost significantly more ambidextrous participants gave "either" answers for the foot than strong left-handers (5.9%), $p = .06$. Ambidextrous participants did not differ from mixed right-handers ($p = .96$) or mixed left-handers ($p = .20$) in this respect. In contrast, ambidextrous participants were not significantly more likely to answer "either" for the eye than the other laterality groups (6.7%, 8.2%, 8.3%, 7.7% and 0% for strong right-handers, mixed right-handers, ambidextrous, mixed left-handers and strong left-handers respectively).

Ambidextrous participants tended to use more their left than their right eye and differed significantly from strong and mixed right-handers in being less likely to use their right eye [strong right-handers: $\chi^2(2) = 7.5$; $p = .023$; mixed

TABLE 7
Frequency of ear preference as a function of handedness

	Strong left-handers (%)	*Mixed left-handers (%)*	*Ambidextrous (%)*	*Mixed right-handers (%)*	*Strong right-handers (%)*
Right ear	0	24.6	30	44.74	57.9
No preference	18.7	31.6	40	34.7	22.4
Left ear	81.2	43.9	30	20.5	19.7

right-handers: $\chi^2(2) = 6.1$; $p = .03$]. In contrast, ambidextrous individuals were more likely to use their right foot than their left foot, and differed from left-handers in being more likely to use their right foot [strong left-handers, $\chi^2(2) = 16.3$; $p < .001$; mixed left-handers, $\chi^2(2) = 12$; $p = .002$]. Thus, the ambidextrous tended to show a left eye preference, like left-handers, and a right foot preference, like right-handers.

For ear preference, there was no difference between ambidextrous and either mixed right-handers or mixed left-handers. Ambidextrous were not significantly more likely to answer "either" for the ear than the other laterality groups (see Table 7). However, the ambidextrous were the only group with about equivalent numbers of right, left and either answers for the ear. When the groups were compared 2 × 2 for ear preference, the ambidextrous differed significantly from strong right-handers who tend to prefer using their right ear, $\chi^2(2) = 6.1$, $p = .04$, and strong left-handers who use mostly their left ear, $\chi^2(2) = 10.5$, $p = .005$, but not from mixed right- or left-handers.

To estimate cross-laterality across the five laterality groups, we compared the side of the hand chosen for the majority of items of the LI with the side of the preferred eye and preferred foot (see Table 6). Across the different laterality groups, between 25% and 50% of participants had eye–hand cross-laterality. A chi-square test on the frequency of eye–hand cross-laterality as a function of laterality group (× 5) showed no significant effect ($p = .35$). However, significantly more ambidextrous individuals were eye–hand cross-lateralized than lateralized participants considered together, $\chi^2(1) = 4.1$, $p = .043$.

Across the different laterality groups, between 3.8% and 29.5% of participants had hand–foot cross-laterality. Foot–hand cross-laterality was significantly less frequent among right-handed participants (5.2%) than among left-handers (25.9%) and the ambidextrous (28.6%). A chi-square test on the frequency of eye–hand cross-laterality as a function of laterality group (× 5) showed that cross-laterality differed significantly among the five groups, $\chi^2(4) = 41.4$; $p < .001$. Pairwise comparisons indicated that the ambidextrous differed significantly from strong right-handers, $\chi^2(1) = 17.3$; $p < .0001$, and from mixed right-handers, $\chi^2(1) = 5.1$; $p = .024$, but not from mixed left-handers ($p = .94$) or from strong left-handers ($p = .36$). In addition, strong right-handers showed significantly less hand–foot cross-laterality than mixed right-handers, $\chi^2(1) = 3.9$; $p = .047$. The difference between strong and mixed left-handers was not significant.

DISCUSSION

The first goal of the present study was to try to find an operational definition of ambidexterity, as opposed to mixed right- or left-handedness and to strong right- and left-handedness. For that purpose, we analysed the responses of 716 adults to a questionnaire including 15 items on hand use in various activities, as well as a few questions on other sensorimotor preferences and personal characteristics. A second, related goal of the study was to try to determine what distinguishes ambidextrous individuals from the more lateralized majority.

A first specific MCA allowed us to define groups of strongly right-handed, strongly left-handed and mixed-handed individuals. A second specific MCA allowed us to distinguish three groups among mixed-handed individuals: the ambidextrous, mixed right-handers and mixed left-handers. Eighty-five per cent of participants were categorized as right-handers (with 56% as strong right-handers and 29.2% as mixed right-handers), 11.5% as left-handers (2.4% of strong left-handers and 9.1% of mixed left-handers) and 3.3% as ambidextrous. We then compared the percentage of individuals categorized as ambidextrous on this analysis with what would have been obtained had we used the main cut-offs mentioned in the literature. In addition, we analysed which participants would be considered as ambidextrous if we set criteria as a function of the number of "either" responses relative to the number of "right" or "left" responses, and as a function of the ratio of "left" to "right" responses (our two criteria for ambidexterity). The best cut-off obtained through these procedures was a [−30, +30] LI cut-off, with a significant correlation of .71 with the MCA categorization. As compared with our lengthy MCA procedure, using a [−30 to +30] cut-off would have categorized 3.1% instead of 3.3% of the study population as ambidextrous. A few participants changed categories (0.1% categorized as mixed right-handed with our MCA became ambidextrous with the −30 to +30 LI cut-off; 0.6% categorized as mixed left-handed became ambidextrous; and 0.98% categorized as ambidextrous became mixed right-handed).

Similarly, we compared the MCA categories of mixed right-handers and mixed left-handers with what would have been obtained had we used the main cut-offs mentioned in the literature. The best-correlated cut-off was a [−90, +90] limit for delimiting mixed left-handedness and mixed right-handedness respectively. We thus suggest the use of [−100 to −90; −89.9 to −29.9; −30 to +30; +30.1 to +89.9 and +90 to +100] as ranges of LI scores to distinguish strong left-handers, mixed left-handers, ambidextrous, mixed right-handers and strong right-handers, respectively.

When all individuals are considered, the items that were least likely to receive an "either hand" answer were using a peeler, writing and using a hammer. For writing and the hammer, this finding is in agreement with previous findings (e.g., Provins et al., 1982; Raczkowski et al., 1974). We were surprised to see that the peeler was the item for which the three groups of handedness answered "either hand" the least often. In fact, only one individual, a mixed right-hander, gave the "either hand" answer. This is interesting given that it is a bimanual item, and bimanual items have often been considered as less lateralized than unimanual items (Raczkowski et al., 1974; see Fagard, 2004, for a review). One reason for this finding may be that the bimanual items used in earlier questionnaires corresponded to actions for which the roles of the two hands are not clearly differentiated, such as using a broom. For the peeler, one hand has to firmly hold the object for the other hand to act on it. It has already been shown with infants that this kind of bimanual action, with complementary and asymmetrical movements of the two hands, induces a strong handedness pattern (Fagard & Marks, 2000).

We then analysed the profile of the participants who were categorized as ambidextrous with our MCA procedure. Ambidexterity was not related to age, but it was related to gender. A significantly higher percentage of males than females were ambidextrous—more than double—and a higher percentage of females than males were right-handed. This result is in line with most of the studies showing less right-hand preference in males than in females (see, for instance, Annett, 1970b). Left-handedness has often been found to be slightly more frequent in males than in females (Cosenza & Mingoti, 1993; Rymar, Kameyama, Niwa, Hiramatsu, & Saitoh, 1984). Here, with left-handers (strong and mixed) being considered apart from ambidextrous, it appears that it is ambidexterity, or lack of clear hand preference, rather than left-handedness, that is more common in males than in females.

Pressure from the family to be right-handed was reported more frequently by ambidextrous individuals than by the lateralized, significantly so in comparison to right-handers and but not left-handers. Thus, it may be that some ambidextrous individuals are former left-handers who were pressured to be right-handed in childhood and ended up ambidextrous as a result.

Significantly more participants reported having a left-handed father than a left-handed mother. This fits with the above-mentioned studies showing a greater proportion of left-handers among males than among females (see Papadatou-Pastou, Martin, Munafo, & Jones, 2008, for a review). However, here the reporting is indirect, and one author who checked reports of parental handedness directly by telephoning the parents found that father's left-handedness tends to be overestimated whereas mother's left-handedness is fairly accurately reported (McKeever, 2000). In our results, left-handedness in one or two parents decreased the frequency of right-handedness and increased the frequency of ambidexterity and left-handedness. Many studies have observed a higher frequency of left-handed children of one left-handed parent, compared to two right-handed parents, and still a higher frequency with two left-handed parents (McKeever, 2000; see Annett, 2008, for a review). Here, we found that having one left-handed parent did not increase the frequency of ambidexterity, but that ambidexterity was more than three times more likely among the offspring of two left-handed parents.

Use of the right foot, the right eye and the right ear decreased regularly and significantly from strong right-handers to strong left-handers. The ambidextrous tended to report a left eye preference, like left-handers, and a right-foot preference, like right-handers. In addition, the ambidextrous differed from the strongly lateralized in more often answering "either" for foot preference, but they were not more likely to answer "either" for the eye. One reason for this pattern may be that the ambidextrous are more lateralized for the eye than for the foot, but it could also be that the response evoked by the two questions is different. Unlike the foot, for which the choice for one side is conscious and can be reported, the choice for one eye is unconscious and had to be tested. We only asked participants to perform one test because we know that the test–retest is very consistent with lateralized persons (Fagard, Monzalvo-Lopez, & Mamassian, 2008). It would be interesting to check whether a test–retest of eye preference would lead to the same consistency in ambidextrous. The ambidextrous did not significantly differ from any other group in the frequency of "either" answers for the ear but, in contrast to the other groups, they were equally likely to answer that they would use the right ear, the left ear, or either one to listen behind a door.

The frequency of eye–hand cross-laterality was comparable in all laterality groups, and the ambidextrous did not differ from more lateralized individuals in this respect. In contrast, foot–hand cross-laterality was significantly more frequent among the ambidextrous than among any other group except mixed left-handers.

In conclusion, we propose that a [−30, +30] cut-off of the LI may be a good way to distinguish a population of ambidextrous individuals from more clearly lateralized individuals, and that [−90] and [+90] may correctly distinguish mixed left- and mixed right-handers from strong handers. Using a precise and simple common criterion to categorize ambidexterity, and in particular to distinguish "ambidextrous" individuals from "mixed" (or "inconsistent") right-handers and left-handers, would be a boon to the study of the relationship between patterns of handedness and cognitive skills. Such a common criterion could make it possible to draw more consistent conclusions from studies on the characteristics associated with ambidexterity during development and in adult cognitive capacities. One further interesting step would be to examine to what extent the individuals categorized as ambidextrous with our procedures would indeed show ambidexterity in a performance evaluation comparing the use of right and left hands.

Manuscript received 18 June 2014
Revised manuscript received 5 December 2014
Revised manuscript accepted 13 January 2015
First published online 11 February 2015

REFERENCES

Annett, M. (1970a). A classification of hand preference by association analysis. *British Journal of Psychology*, *61*, 303–321. doi:10.1111/j.2044-8295.1970.tb01248.x

Annett, M. (1970b). The growth of manual performance and speed. *British Journal of Psychology*, *61*, 545–558. doi:10.1111/j.2044-8295.1970.tb01274.x

Annett, M. (1976). A coordination of hand preference and skill replicated. *British Journal of Psychology*, *67*, 587–592. doi:10.1111/j.2044-8295.1976.tb01550.x

Annett, M. (1992). Five tests of hand skill. *Cortex*, *28*, 583–600. doi:10.1016/S0010-9452(13)80229-8

Annett, M. (1998). Handedness and cerebral dominance: The right shift theory. *Journal of Neuropsychiatry and Clinical Neurosciences*, *10*, 459–469. doi:10.1176/jnp.10.4.459

Annett, M. (2008). Tests of the right shift genetic model for two new samples of family handedness and for the data of McKeever (2000). *Laterality*, *13*(2), 105–123.

Annett, M., & Kilshaw, D. (1982). Mathematical ability and lateral asymmetry. *Cortex*, *18*, 547–568. doi:10.1016/S0010-9452(82)80053-1

Auer, T., Pinter, S., Kovacs, N., Kalmar, Z., Nagy, F., Horvath, R. A., … Janszky, J. (2009). Does obstetric brachial plexus injury influence speech dominance? *Annals of Neurology*, *65*(1), 57–66. doi:10.1002/ana.21538

Barut, C., Ozer, C. M., Sevinc, O., Gumus, M., & Yunten, Z. (2007). Relationships between hand and foot preferences. *International Journal of Neuroscience*, *117*, 177–185. doi:10.1080/00207450600582033

Batheja, M., & McManus, I. C. (1985). Handedness in the mentally handicapped. *Developmental Medicine and Child Neurology*, *27*(1), 63–68. doi:10.1111/j.1469-8749.1985.tb04526.x

Benbow, C. P. (1986). Physiological correlates of extreme intellectual precocity. *Neuropsychologia*, *24*, 719–725. doi:10.1016/0028-3932(86)90011-4

Benbow, C. P. (1987). Possible biological correlates of precocious mathematical reasoning ability. *Trends in Neurosciences*, *10*(1), 17–20. doi:10.1016/0166-2236(87)90117-2

Benzécri, J.-P. (1992). *Correspondence analysis handbook*. New York: Dekker.

Bryden, P. J., Bruyn, J., & Fletcher, P. (2005). Handedness and health: An examination of the association between different handedness classifications and health disorders. *Laterality*, *10*, 429–440.

Bryden, P. J., Pryde, K. M., & Roy, E. A. (1999). Preferential reaching into hemispace: An examination of performance, preference, and task complexity. *Brain and Cognition*, *40*(1), 64–67.

Bryden, P. J., Pryde, K. M., & Roy, E. A. (2000). A performance measure of the degree of hand preference. *Brain and Cognition*, *44*, 402–414. doi:10.1006/brcg.1999.1201

Bryden, P. J., & Roy, E. A. (2006). Preferential reaching across regions of hemispace in adults and children. *Developmental Psychobiology*, *48*(2), 121–132. doi:10.1002/dev.20120

Büsch, D., Hagemann, N., & Bender, N. (2010). The dimensionality of the Edinburgh Handedness Inventory: An analysis with models of the item response theory. *Laterality*, *15*(6), 610–628. doi:10.1080/13576500903081806

Cabinio, M., Blasi, V., Borroni, P., Montagna, M., Iadanza, A., Falini, A., & Cerri, G. (2010). The shape of motor resonance: Right- or left-handed? *NeuroImage*, *51*(1), 313–323. doi:10.1016/j.neuroimage.2010.01.103

Carlier, M., Doyen, A.-L., & Lamard, C. (2006). Midline crossing: Developmental trend from 3 to 10 years of age in a preferential card-reaching task. *Brain and Cognition*, *61*, 255–261. doi:10.1016/j.bandc.2006.01.007

Carlier, M., Stefanini, S., Deruelle, C., Volterra, V., Doyen, A.-L., Lamard, C., … Fisch, G. (2006). Laterality in persons with intellectual disability. I – Do patients with trisomy 21 and Williams-Beuren syndrome differ from typically developing persons? *Behavior Genetics*, *36*, 365–376. doi:10.1007/s10519-006-9048-9

Corballis, M. C., Hattie, J., & Fletcher, R. (2008). Handedness and intellectual achievement: An even-handed look. *Neuropsychologia*, *46*, 374–378. doi:10.1016/j.neuropsychologia.2007.09.009

Coren, S., & Porac, C. (1978). The validity and reliability of self-report items for the measurement of lateral preference. *British Journal of Psychology*, *69*, 207–211. doi:10.1111/j.2044-8295.1978.tb01649.x
Corey, D. M., Hurley, M. M., & Foundas, A. L. (2001). Right and left handedness defined: A multivariate approach using hand preference and hand performance measures. *Neuropsychiatry, Neuropsychology, and Behavioral Neurology*, *14*, 144–152.
Cornish, K. M., & McManus, I. C. (1996). Hand preference and hand skill in children with autism. *Journal of Autism and Developmental Disorders*, *26*, 597–609. doi:10.1007/BF02172349
Cosenza, R. M., & Mingoti, S. A. (1993). Career choice and handedness: A survey among university applicants. *Neuropsychologia*, *31*, 487–497. doi:10.1016/0028-3932(93)90062-5
Crow, T. J., Crow, L. R., Done, D. J., & Leask, S. (1998). Relative hand skills predicts academic ability: Global deficits at the point of hemispheric indecision. *Neuropsychologia*, *36*, 1275–1282. doi:10.1016/S0028-3932(98)00039-6
Denny, K. (2008). Cognitive ability and continuous measures of relative hand skill: A note. *Neuropsychologia*, *46*, 2091–2094. doi:10.1016/j.neuropsychologia.2008.02.004
Domellöf, E., Rönnqvist, L., Titran, M., Esseily, R., & Fagard, J. (2009). Atypical functional lateralization in children with fetal alcohol syndrome. *Developmental Psychology*, *51*, 696–705.
Dragovic, M., & Hammond, G. (2007). A classification of handedness using the Annett Hand Preference Questionnaire. *British Journal of Psychology*, *98*, 375–387. doi:10.1348/000712606X146197
Fagard, J. (2004). Latéralités et asymétries: définitions et mesures [Lateralities and asymmetries: Definitions and measurements]. In J. Fagard (Ed.), *Droitiers/Gauchers: des asymétries dans tous les sens* [Right-handers/Left-handers: Asymmetries everywhere] (pp. 15–48). Marseille: Solal.
Fagard, J., & Marks, A. (2000). Unimanual and bimanual tasks and the assessment of handedness in toddlers. *Developmental Science*, *3*(2), 137–147. doi:10.1111/1467-7687.00107
Fagard, J., Monzalvo-Lopez, K., & Mamassian, P. (2008). Relationship between eye preference and binocular rivalry, and between eye-hand preference and reading ability in children. *Developmental Psychobiology*, *50*, 789–798. doi:10.1002/dev.20328
Gardner, M. R., & Potts, R. (2010). Hand dominance influences the processing of observed bodies. *Brain and Cognition*, *73*(1), 35–40. doi:10.1016/j.bandc.2010.02.002
Giotakos, O. (2002). Crossed hand-eye dominance in male psychiatric patients. *Perceptual and Motor Skills*, *95*, 728–732. doi:10.2466/pms.2002.95.3.728
Halpern, D. F., Haviland, M. G., & Killian, C. D. (1998). Handedness and sex differences in intelligence: Evidence from the medical college admission test. *Brain and Cognition*, *38*(1), 87–101. doi:10.1006/brcg.1998.1021
Hatta, T., & Kawakami, A. (1995). Patterns of handedness in modern Japanese: A cohort effect shown by re-administration of the H.N. Handedness Inventory after 20 years. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, *49*, 505–512. doi:10.1037/1196-1961.49.4.505
Johnston, D. W., Nicholls, M. E. R., Shah, M., & Shields, M. A. (2009). Nature's experiment? Handedness and early childhood development. *Demography*, *46*, 281–301. doi:10.1353/dem.0.0053
Knecht, S., Drager, B., Deppe, M., Bobe, L., Lohmann, H., Floel, A., … Henningsen, H. (2000). Handedness and hemispheric language dominance in healthy humans. *Brain*, *123*(12), 2512–2518. doi:10.1093/brain/123.12.2512
Kopiez, R., Galley, N., & Lee, J. I. (2006). The advantage of a decreasing right-hand superiority: The influence of laterality on a selected musical skill (sight reading achievement). *Neuropsychologia*, *44*, 1079–1087. doi:10.1016/j.neuropsychologia.2005.10.023
Leconte, P., & Fagard, J. (2004). Influence of object spatial location and task complexity on children's use of their preferred hand depending on their handedness consistency. *Developmental Psychobiology*, *45*(2), 51–58. doi:10.1002/dev.20019
Le Roux, B., & Rouanet, H. (2004). *Geometric data analysis: From correspondence analysis to structured data analysis*. Dordrecht: Kluwer Academic.

Le Roux, B., & Rouanet, H. (2010). Multiple correspondence analysis. QASS Series. Thousand Oaks, CA: Sage.

Li, C., Zhu, W., & Nuttall, R. L. (2003). Familial handedness and spatial ability: A study with Chinese students aged 14–24. *Brain and Cognition*, *51*, 375–384. doi:10.1016/S0278-2626(03)00041-1

Mayringer, H., & Wimmer, H. (2002). No deficits at the point of hemispheric indecision. *Neuropsychologia*, *40*, 701–704. doi:10.1016/S0028-3932(01)00191-9

McKeever, W. F. (1986). The influences of handedness, sex, familial sinistrality and androgyny on language laterality, verbal-ability, and spatial ability. *Cortex*, *22*, 521–537. doi:10.1016/S0010-9452(86)80013-2

McKeever, W. F. (2000). A new family handedness sample with findings consistent with X-linked transmission. *British Journal of Psychology*, *91*(1), 21–39. doi:10.1348/000712600161655

McManus, C. (2002). *Right hand, left hand: The origins of asymmetry in brains, bodies, atoms and cultures*. London: Weidenfeld & Nicolson.

McMeekan, E. R., & Lishman, W. A. (1975). Retest reliabilities and interrelationship of the Annett hand preference questionnaire and the Edinburgh Handedness Inventory. *British Journal of Psychology*, *66*(1), 53–59. doi:10.1111/j.2044-8295.1975.tb01439.x

Mori, S., Iteya, M., & Gabbard, C. (2006). Hand preference consistency and eye-hand coordination in young children during a motor task. *Perceptual and Motor Skills*, *102*(1), 29–34. doi:10.2466/pms.102.1.29-34

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia*, *9*(1), 97–113. doi:10.1016/0028-3932(71)90067-4

Orton, S. T. (1937). *Reading, writing, and speech problems in children*. New York, NY: W.W. Norton.

Papadatou-Pastou, M., Martin, M., & Munafò, M. R. (2013). Measuring hand preference: A comparison among different response formats using a selected sample. *Laterality*, *18*(1), 68–107.

Papadatou-Pastou, M., Martin, M., Munafo, M. R., & Jones, G. V. (2008). Sex differences in left-handedness: A meta-analysis of 144 studies. *Psychological Bulletin*, *134*, 677–699. doi:10.1037/a0012814

Peters, M., Reimers, S., & Manning, J. T. (2006). Hand preference for writing and associations with selected demographic and behavioral variables in 255,100 subjects: The BBC internet study. *Brain and Cognition*, *62*, 177–189. doi:10.1016/j.bandc.2006.04.005

Peters, M., & Servos, P. (1989). Performance of subgroups of left-handers and right-handers. *Canadian Journal of Psychology/Revue canadienne de psychologie*, *43*, 341–358. doi:10.1037/h0084226

Ponton, C. W. (1987). Enhanced articulatory speed in ambidexters. *Neuropsychologia*, *25*, 305–311. doi:10.1016/0028-3932(87)90144-8

Prichard, E., Propper, R. E., & Christman, S. D. (2013). Degree of handedness, but not direction, is a systematic predictor of cognitive performance. *Frontiers in Psychology*, *4*, 9. doi:10.3389/fpsyg.2013.00009

Provins, K. A., Milner, A. D., & Kerr, P. (1982). Asymmetry of manual preference and performance. *Perceptual and Motor Skills*, *54*, 179–194. doi:10.2466/pms.1982.54.1.179

Raczkowski, D., Kalat, J. W., & Nebes, R. (1974). Reliability and validity of some handedness questionnaire items. *Neuropsychologia*, *12*(1), 43–47. doi:10.1016/0028-3932(74)90025-6

Rodriguez, A., Kaakinen, M., Moilanen, I., Taanila, A., McGough, J. J., Loo, S., & Jarvelin, M.-R. (2010). Mixed-handedness is linked to mental health problems in children and adolescents. *Pediatrics*, *125*, e340–e348. doi:10.1542/peds.2009-1165

Rymar, K., Kameyama, T., Niwa, S., Hiramatsu, K., & Saitoh, O. (1984). Hand and eye preference patterns in elementary and junior high school students. *Cortex*, *20*, 441–446. doi:10.1016/S0010-9452(84)80013-1

Satz, P., & Green, M. F. (1999). Atypical handedness in schizophrenia: Some methodological and theoretical issues. *Schizophrenia Bulletin*, *25*(1), 63–78. doi:10.1093/oxfordjournals.schbul.a033367

Slezicki, K. I., Cho, Y. W., Yi, S. D., Brock, M. S., Pfeiffer, M. H., McVearry, K. M., … Motamedi, G. K. (2009). Incidence of atypical handedness in epilepsy and its association with clinical factors. *Epilepsy and Behavior*, *16*, 330–334. doi:10.1016/j.yebeh.2009.08.006

Soper, H. V. (1986). Handedness patterns in autism suggest subtypes. *Journal of Autism and Developmental Disorders*, *16*, 155–167. doi:10.1007/BF01531727

Steenhuis, R. E., & Bryden, M. P. (1989). Different dimensions of hand preference that relate to skilled and unskilled activities. *Cortex*, *25*, 289–304. doi:10.1016/S0010-9452(89)80044-9

Szaflarski, J. P., Binder, J. R., Possing, E. T., McKiernan, K. A., Ward, B. D., & Hammeke, T. A. (2002). Language lateralization in left-handed and ambidextrous people: fMRI data. *Neurology*, *59*, 238–244. doi:10.1212/WNL.59.2.238